

UCRL-7052

D-26C
UCRL 7052

University of California
Ernest O. Lawrence
Radiation Laboratory

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

20011015 097

THE STATUS OF TRANSPORT PROPERTIES OF AIR

LOVELACE FOUNDATION
FOR MEDICAL EDUCATION and RESEARCH
DEPARTMENT OF AEROSPACE MEDICINE
AND BIOASTRONAUTICS

Livermore, California

Reproduced From
Best Available Copy

UCRL-7052
Propulsion Systems and
Energy Conversion, UC-33
TID-4500 (18th Ed.)

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

THE STATUS OF TRANSPORT PROPERTIES OF AIR

V. E. Schrock

September 25, 1962

Printed in USA. Price 75 cents. Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D.C.

NOMENCLATURE

c_v	Constant-volume specific heat
c_p	Constant-pressure specific heat
D	Diameter
f	Property group $c_v \eta / k$
g_c	Gravitational constant
k	Boltzmann constant
k	Thermal conductivity
\dot{m}	Mass flow rate
M	Molecular weight
p	Pressure
Pr	Prandtl number
\vec{r}	Distance from center of mass
T	Temperature
V	Volume
x	Distance along tube
γ	c_p / c_v
ϵ	Energy parameter
η	Viscosity
ρ	Density
ϕ	Force potential for molecular encounters
Ω	Transport integral defined in Eq. (4)

THE STATUS OF TRANSPORT PROPERTIES OF AIR

V. E. Schrock*

Department of Nuclear Engineering, University of California

Berkeley, California

September 25, 1962

I. INTRODUCTION

As materials technology permits higher temperature operation of propulsion equipment, accuracy of performance predictions becomes lower due to uncertainty in the physical properties of materials. Of particular concern in jet-propulsion devices are of course the properties of gases. Thermodynamic functions, are known to a comparatively high degree of accuracy. Transport properties, viscosity, thermal conductivity, and the mass diffusion coefficients, are difficult to measure with a high degree of accuracy and therefore are not as well known, particularly at high temperature. Viscosity, thermal conductivity, and Prandtl number are of primary importance in high-temperature heat transfer to gases. The purpose of this report is to explore the status of experimental data for air and to review the measurement problem and techniques and the predictions available from the general transport theory of Boltzmann. Because the constant-pressure specific heat is known to a high degree of accuracy, the Prandtl number $c_p \eta / k$ is customarily calculated from it and the best available viscosity and thermal conductivity. For this reason emphasis is given here to viscosity and thermal conductivity.

II. THEORETICAL PREDICTION OF THERMAL CONDUCTIVITY AND VISCOSITY

Maxwell and Boltzmann established the general transport equation for the kinetic theory of gases. This theory is described in great detail by Chapman and Cowling¹ and Hirschfelder et al.² Chapman and Enskog independently obtained solutions for the transport properties. These solutions

*Consultant to "R" Division, Lawrence Radiation Laboratory, Livermore.

are rigorous for dilute monatomic gases, but are approximate to some degree for the more complex polyatomic molecules. The process of momentum exchange, characterized by viscosity, is predicted with negligible error at ordinary temperature for the polyatomic gas because internal modes of motion play a relatively unimportant role in momentum consideration. In the case of thermal conductivity (energy transport) the internal motions are very important and the theory must be corrected to yield suitable results even at moderate temperatures. The correction factor was first derived by Eucken³ by consideration of transfer of energy between translational and internal (rotation and vibration) modes.

As the temperature increases, all transport properties, particularly the thermal conductivity, become less certain theoretically. This is apparently due to lack of understanding of the fundamental force potential for molecular encounters. Since this potential is not directly measurable, it is commonly inferred from transport properties and this interest, among others, has helped to stimulate interest in accurate direct measurements of transport properties. Several models have been proposed for the force potential, e. g. , Lennard-Jones, Sutherland, Buckingham, etc. , but so far none has proven entirely satisfactory nor is there general agreement as to which potential is most nearly correct.

From the Chapman-Enskog solution the relation between viscosity and thermal conductivity is, to the first approximation:

$$k = f c_v \eta \quad (1)$$

where k is the thermal conductivity, c_v is the constant-volume specific heat, η is the viscosity, and the factor $f = 5/2$ for spherically symmetric non-rotating molecules. For higher approximations f approaches 2.522. For rotating molecules (considering internal modes only) $f = 1$, so the actual value is between 1 and 2.522.

It might be worthwhile to note that the factor f is related to Prandtl number, i. e. ,

$$Pr = \gamma / f \quad (2)$$

where $\gamma = c_p / c_v$, the specific heat ratio.

The Eucken correction for polyatomic molecules is based on the additive values of f for internal motion and f for translation with their contributions determined by γ so that

$$k = (1/4)(9\gamma - 5)c_v\eta \quad (3)$$

for polyatomic molecules. Chapman and Cowling question the separability of the translational and internal contributions. In essence, thermal conductivity is more complicated due to the sensitive dependence of transition probabilities for the transfer of energy between various degrees of freedom of the molecule and the effect this has upon energy exchange between molecules experiencing inelastic collisions. The Eucken correction is an approximation which assumes rapid transfer such that the energy distribution among molecular states is essentially the equilibrium distribution corresponding to the local temperature.

Bromley³⁷ extended the Eucken correction by considering more detail of the internal energy modes. Internal rotation was considered separately from overall rotation and vibration. Electronic transitions were also included. The resulting equation for the factor $f = k/c_v\eta$ in the pressure-independent range (low pressure) includes temperature dependence.

In the kinetic theory (dilute gas) prediction of the transport coefficients the integral transport equations based on the conservation principles are solved by expanding scalar functions in Sonine polynomials which depend upon a double integral*

$$\Omega^{(l,s)} = \frac{2\pi kT}{\mu_{ij}} \int_0^\infty \int_0^\infty e^{-\gamma_{ij}^2} \gamma_{ij}^{2s+3} (1 - \cos^l \chi) b \, db \, d\gamma_{ij} \quad (4)$$

This is written for a collision between molecules of types i and j ; μ_{ij} is the reduced mass of the colliding pair, γ_{ij} is the reduced initial relative speed of the colliding molecules, χ is the angle of deflection in the center-of-mass system, and b is the impact parameter (distance between molecules at the projected closest point of approach). Parameters are tabulated in Hirschfelder, et al.

*For details see Hirschfelder, et al. Ref. 2.

The theory predicts the transport properties in terms of $\Omega^{(\ell, s)}$ and properties of the potential functions which are of the general form:

$$\phi(\vec{r}) = \epsilon f\left(\frac{\vec{r}}{\sigma}\right) \quad (5)$$

in which ϵ is the energy constant and σ is the molecular diameter. Thus, for coefficient of shear viscosity of a pure gas

$$[\eta]_k = [\eta]_1 f_\eta(k) \quad (6)$$

where $[\eta]_1$, is the first order approximation,

$$[\eta]_1 \times 10^7 = 266.93 \frac{\sqrt{M/T}}{\sigma^2 \Omega^{(2,2)} T^*} \quad (\text{poise}) \quad (7)$$

where

M is molecular weight

T is temp., °K

$T^* = kT/\epsilon$

σ = collision diameter, Å

* on $\Omega^{(2,2)}$ refers to normalization to the hard sphere value of $\Omega^{(2,2)}$.

The correction $f_\eta(k)$ is a slowly varying function of T^* and is given in Chapter 8 of Hirschfelder. In the case of binary gases (air approximately) this result is complicated by collisions between unlike species and may be treated by methods described by Hirschfelder.

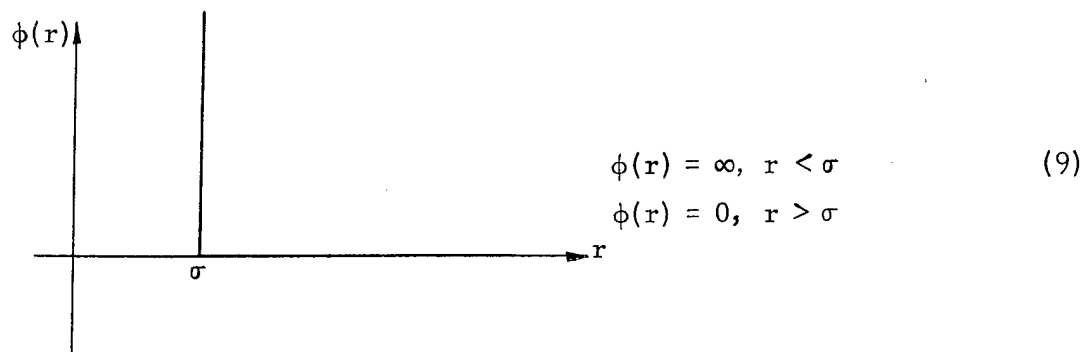
Thermal conductivity is given by

$$[k]_k = f_k(k) [k]_1 \quad \text{with}$$

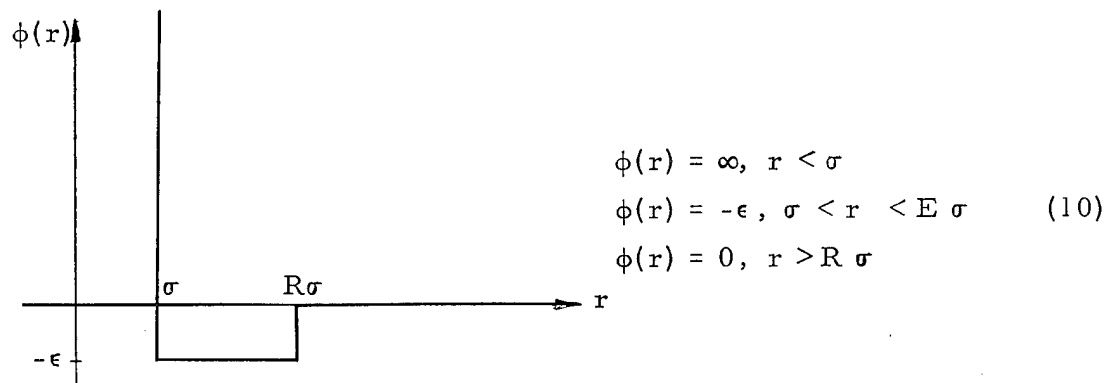
$$[k]_1 \times 10^7 = 1989.1 \frac{\sqrt{T/M}}{\sigma^2 \Omega^{(2,2)} T^*} \quad (\text{cal/cm sec}) \quad (8)$$

where $f_k(k)$ differs from $f_\eta(k)$ as explained above and approximately by the Eucken correction. For the binary mixture (multicomponent mixture in general) the expression is again more complex because of collisions of various types which are possible.

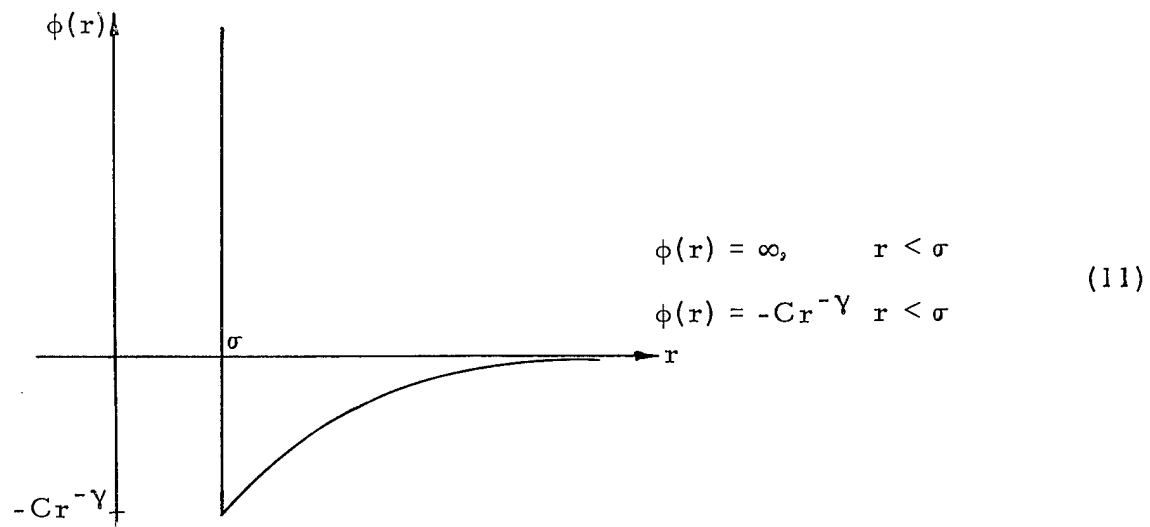
A. Rigid Sphere

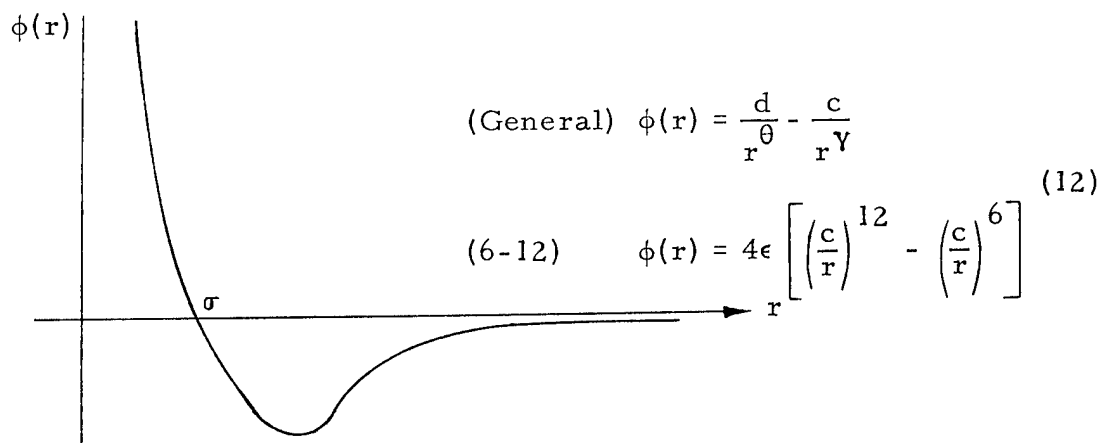
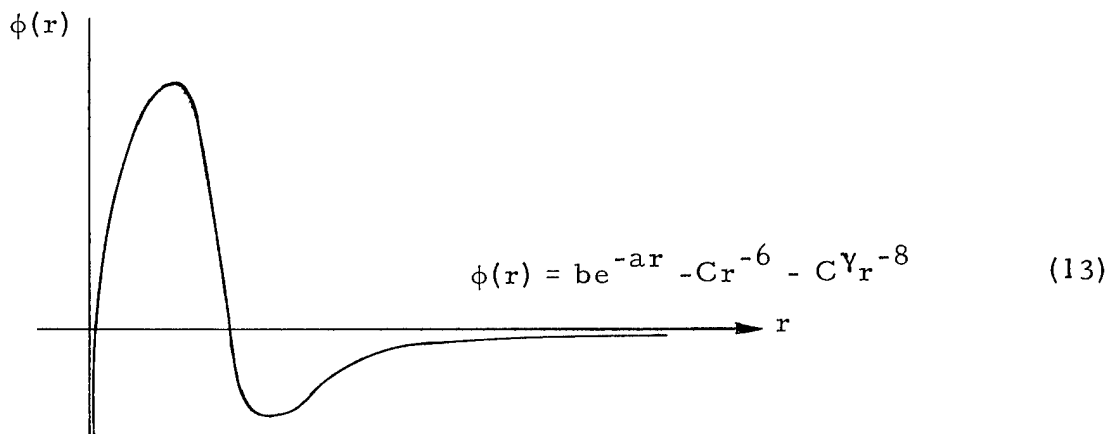


B. Square Well



C. Sutherland



D. Lennard-JonesE. BuckinghamF. Modified Buckingham

$$\phi(r) = \frac{\epsilon}{1 - 6/a} \left\{ \frac{6}{a} \exp \left[a \left(1 - \frac{r}{r_m} \right) - \left(\frac{r_m}{r} \right)^6 \right] \right\}, \quad r \geq r_{\max} \quad (14)$$

$$\phi(r) = \infty, \quad r \leq r_{\max}$$

where r_m is the value for the energy minimum

a is the steepness of the exponential functions (13.5)

r_{\max} is the value for $\max \phi(r)$

ϵ is the depth of the potential well.

In each case there are involved molecular parameters (ϵ and σ) which are characteristic of the specie and which must be deduced from empirical values of one of the macroscopic properties (e.g., viscosity). In a

sense, then, the theory does not provide predictions, but interpolation and extrapolation or interrelation of various properties. Hirschfelder, et al., (Chapter 8 and Appendix) give extensive values of the force constants. These are most frequently determined from measured viscosity. In addition, comparisons are given between calculated and measured viscosity in the high-temperature range for some pure gas. It appears that, for example, force constants can be chosen for the Lennard-Jones (6 - 12) potential which result in agreement within 1% between the predicted and measured viscosity of nitrogen (at 1 atm) in the temperature range 100 to 1100°K. All of the potential forms are capable of accurate predictions (or fitting of the data) in the low-temperature range 100 to 400°K.

The theory of the dilute gas has also been extended to the dense gas case and predictions of the effect of pressure upon the viscosity and thermal conductivity can be made with reasonable accuracy. In general the transport properties depend much more strongly upon temperature than pressure.

III. EXPERIMENTAL METHODS

A. Viscosity

Measurements of transport properties are usually based on the solution of a basic general equation for such a simple geometry and boundary conditions that an exact solution exists. The system must be chosen to give close approach to the ideal conditions and the solution must relate the property to be measured only to quantities which may be directly measured with suitable accuracy. Thus, to measure viscosity, solutions of the Navier-Stokes equations are employed; while for thermal conductivity, solutions of the Fourier equation are used. One-dimensional (or very simple two-dimensional) geometries are almost invariably selected for accurate measurements.

Viscosity is usually measured by techniques which may be classified as one of the following:

1. Capillary tubes
2. Rotating cylinder
3. Rotating disk
4. Falling sphere
5. Orifice flow
6. Flow in porous media.

Capillary Tubes

The principle of the capillary tube measurement rests on the Hagen-Poiseuille solution of the Navier-Stokes equations applied to flow in a circular pipe. This solution predicts

$$\eta = \frac{\pi g_c \rho D^4}{32 \dot{m}} \left(-\frac{dp}{dx} \right), \quad (15)$$

The measurements to be made are of ρ , D , \dot{m} and $(-dp/dx)$. Since D appears to the fourth power it must be measured with great precision. Accuracy between 1/4 and 1/2% appears feasible when such an experiment is done with great care and the best instrumentation. Some experimenters have coiled the capillary so that greater length could be used conveniently. In precision work this should be avoided because of the obvious departure from the conditions of Hagen-Poiseuille flow. It is desirable to make the tube long enough so as to produce a pressure gradient large enough to measure accurately, but not so long that the density of the gas changes appreciably.

The capillary method is suitable for use with both gases and liquids and may be used at high temperatures and pressure. In any case, the pressure taps must be free from burrs and the entrance and exit regions avoided to ensure adherence to the Hagen-Poiseuille flow condition.

Rotating Cylinder or Disk

Solutions are available for these geometries which are essentially exact. They are omitted here for brevity. In each case it is necessary to measure torque, rotational speed, dimensions of the apparatus, and the state of the fluid. Edge effects present problems as does concentricity of the parts. However, this technique has been used very successfully in producing precision data at ambient pressure and temperature. For high-pressure work it is difficult to handle a precision, rotating device. At high temperatures it may also be difficult to maintain the necessary dimensional control.

Falling Sphere, Orifice, Porous Media

These techniques are not based upon exact solutions of the N-S equations and consequently are to be regarded as secondary or comparison

methods. It is necessary to calibrate the device with a fluid of known viscosity. The falling sphere and orifice techniques are used with incompressible fluids, while the porous media may be used for gases.

B. Thermal Conductivity

Thermal conductivity meters or cells are designed around simple, one-dimensional geometries (slabs, cylinders, or spheres) for which the solution to the Fourier conduction equation in the steady state or transient case is well known. In any case the measurements to be made include heat flow, temperatures, and the dimensions of the cell, together with the state of the fluid. A chief difficulty in all cases is the conflicting requirement of using substantial temperature differences to get suitable accuracy and of using small enough differences to avoid thermal convection (mass motion superimposed on molecular motion).

In the case of gases, the measurements are particularly difficult because the low thermal conductivity and the resulting small heat flux, which demands greater accuracy in the correction for end or edge losses. In the high-temperature range, there is the added difficulty of thermal radiation becoming a significant part of the heat exchange between the confining surfaces. All cell designs attempt to make the best compromise of these factors for the specific fluid and conditions of interest.

Hot-wire cells consist of a fine wire mounted axially in a hollow cylinder. The wire serves both as a heater and a resistance thermometer. This simple device was modified by Eucken³ to automatically compensate for end losses. The chief difficulties lie in the concentricity and extreme dimensional accuracy required if the cell is to be used for absolute measurements. These requirements are not so severe when the apparatus is to be used to measure relative values. Measurement of the temperature of the outer surface is also difficult. The hot wire has, however, been one of the most successful techniques for use with gases.

Concentric cylinders have also been employed. Kannuliik and Martin⁴ used a thick wire in a hot-wire apparatus to reduce the uncertainty in wire mean diameter and to reduce the variation of heat flux at the wire surface. Glassman and Bonilla,⁵ Keyes and Sandill,⁶ and Vines⁷ have recently used the concentric cylinder in the high-temperature region. Glassman and

Bonilla employed a quartz outer cylinder to avoid radiation effects. Levinson⁸ designed a concentric cylinder device to operate at 3000°F, however it was never built.

Parallel plates have also been used extensively for gases. With horizontal orientation of the plates and downward heating, static stability of the gas is maintained with large temperature differences. However, guard heaters are necessary to control edge losses.

Concentric spheres are ideally suited to measurement of conductivity of liquids and were used for many early measurements on gases. The chief virtue of this configuration is the minimization of heat leakage which takes place only through spacers, thermocouple, and heater leads. For liquids the spacers may be made of material having comparable conductivities, but for gases the spacers are bound to carry a significant portion of the heat input. The other disadvantage is the difficulty and high cost of fabricating precision spheres of suitable size.

Secondary or indirect methods have also been proposed, e. g. , Eckert and Irvine,⁹ proposed measuring Prandtl number and then calculating thermal conductivity from known viscosity and density data, the latter two properties being better known and measured with less difficulty. They proposed measuring recovery factors for laminar boundary layer flow over a flat plate. Pohlhausen obtained the solution to this problem for the constant fluid properties case and Buseman showed that the recovery factor was just $Pr^{1/2}$. This solution of course contains the boundary layer assumptions, but this is not serious to the accuracy desired in the measured Pr . Eckert and Irvine employed a probe in a converging nozzle to measure the Prandtl number of air. High accuracy (1/2%) is claimed in calculated thermal conductivity based on these Prandtl number data.

IV. EXPERIMENTAL RESULTS

A. Viscosity

The Table of Gas Properties¹⁰ compiled by the National Bureau of Standards gives averaged 1-atm viscosity data for air based on references 11 through 21. The constants in a Sutherland-type equation

$$\eta \times 10^7 = \frac{AT^{3/2}}{T + B} \quad (\text{poise}) \quad (16)$$

based on these data were found to be $A = 145.8$ and $B = 110.4$. The tabulated data are in the form η/η_0 with $\eta_0 = 1716 \times 10^{-7}$ poise and are calculated from Eq. (16). These values are compared graphically with the data cited above and are shown to agree within 1/2% with all the data of Vasilesco¹¹ in the temperature range $100 < T^\circ\text{K} < 1900$. The other observer's data agree within 2-1/2% as a whole (below 800°K). No data are given for elevated pressure.

The NBS tabulation was based on all the available data known to the authors and presumably reflects some judgment in weighting the data. The absolute accuracy of course cannot be determined. It is strange, however, that the data of Bearden²² were omitted from this tabulation. Bearden measured the viscosity of air in order to improve the evaluation of the fundamental electronic charge by the Millikan oil-drop and x-ray methods. He claimed accuracy in viscosity of 3 parts in 10^5 , which is of an entirely different order from the data in the NBS compilation. Bearden's work was done at standard conditions minimizing experimental problems, but the meticulous care in the experiment is impressive none-the-less. One would certainly wonder at the omission by NBS of such excellent work. The data compare as follows:

$$\begin{array}{ll} \text{@ } 293^\circ\text{K} & \text{Bearden } \eta = (1812.26 \pm 0.06) \times 10^{-7} \text{ poise} \\ & \text{NBS } \eta = 1819.20 \times 10^{-7} \text{ poise.} \end{array}$$

The two differ by 0.39%. In view of the quality of Bearden's work it would seem appropriate to force Eq. (16) to pass through his data. Comparison with Vasilesco's data, which are the most extensive, would not be seriously degraded.

Absolute accuracy is very difficult to assess, but it would appear that the viscosity of air at 1 atmosphere and 20°C is known to within a small fraction of 1%, and that at elevated temperature (to 1900°K) it is known to within about 1/2%. One point that must be stressed is that moisture content and other variations in the composition of "air" may have considerable effect upon the viscosity.

The effect of pressure upon viscosity has been measured by Kestin and Wong²³ and Kestin and Persen²⁴ using an oscillating disk viscosimeter. The apparatus was calibrated against the nitrogen data of Michels and Gibson²⁵ who used a Rankine capillary apparatus. The former measured viscosity to

80 atm, while the latter went to 1000 atm, but both sets of data were for moderate temperatures. It appears that the only means presently available for getting viscosity at both elevated pressure and temperature is by calculation using methods described in Chapter 9 of Hirschfelder et al. and the method of corresponding states, which has some basis in experiment from the data of Uhler²⁶ for carbon dioxide over a wide range of pressure and temperature. There is good agreement between the pressure effect calculations and data of Michels and Gibson for nitrogen and Warburg and Babo²⁷ for carbon dioxide. The effect of pressure on viscosity of air is roughly an increase of 10% per 100-atm increase in pressure at 25°C, according to the data of Kestin, et al. Values calculated by Granet and Kass³⁵ based on the law of corresponding states predicts a somewhat stronger dependence on pressure as shown in Table I. Biles and Putnam³⁶ give high data for air at 75°F and 517°F for pressures to 850 psi. These data were obtained in a porous medium.

B. Thermal Conductivity

NBS 564 tabulates values of thermal conductivity of air at 1 atmosphere from the Sutherland type equation.

$$k = \frac{a\sqrt{T}}{1 + \frac{b \times 10^{-5}(C/T)}{T}} \quad (\text{cal/sec cm}) \quad (17)$$

with $a = 0.6325 \times 10^{-5}$
 $b = 245.4$
 $c = 12.$

Equation (17) is based on the weighted average of the data of references 28 through 33. Comparison with the computed values from Eq. (17) shows the data to scatter in the range of +7.6% to -4%. The authors feel the absolute accuracy is within 5%. Eckert and Irvine⁹ claim their results based on Prandtl number measurement have an absolute accuracy of 1/2%. This is probably optimistic since the viscosity data used in the calculations are uncertain to that degree.

The best available data appear to be those of Stops³⁴ who made measurements in a quartz-platinum hot-wire cell to 1000°C. He found that his

data followed a Sutherland form up to 600°C, but could not fit any viscosity-temperature relation above that level.

The effect of pressure on thermal conductivity of gases has been measured by Lenoir,³⁸ Frank,³⁹ and Kannuluik and Donald.⁴⁰ Comings and Nathan⁴¹ have developed a generalized correlation based on the law of corresponding states and substantiated by the data of Lenoir. Granet and Kass³⁵ developed graphs of thermal conductivity (and viscosity) for dry air based on the low-pressure data of NBS 564 and the correlations of Gamson⁴² and Uyehara and Watson.⁴³ The calculated pressure effect is illustrated in Table I.

Table I. Effect of pressure on thermal conductivity and viscosity of dry air (from Granet and Kass, Ref. 35).

Temp (°F)	% increase for 2000 psi above ambient	
	k	η
100	26.0	26.6
500	8.1	4.5
1000	4.6	2.0
1500	4.4	2.5

The knowledge of thermal conductivity of air is considerably poorer than for viscosity. Here again the region of greatest uncertainty is for combined high pressure and high temperature. For gas mixtures, such as air, there has been some speculation that mass diffusion due to a temperature gradient may have some effect on measurements of thermal conductivity. Such an effect would be very important in heat transfer to gases with very large temperature differences.

A more extensive list of references for work on both thermal conductivity and viscosity is given by Touloukian⁴⁴ in the Retrieval Guide. These two sets of references are included here for convenience as a supplementary bibliography.

V. CONCLUSION

There is considerable need for new experimental and theoretical work in the area of high pressure and temperature transport properties. The need

is greatest for thermal conductivity, although viscosity data at simultaneously high temperature and pressure are almost totally lacking. New techniques are needed for the measurement of thermal conductivity at high temperature which are not seriously hampered by thermal radiation acting in parallel. In this regard the experiments of Eckert and Irvine are very promising. All new high-precision experiments should be done with air of accurately determined composition. There is also need of a recognized, standard composition of air for this purpose.

VI. BIBLIOGRAPHY

1. Chapman and Cowling, "The Mathematical Theory of Non-Uniform Gases," Cambridge Univ. Press. Cambridge, England (1951).
2. Hirschfelder, Curtiss and Bird, "Molecular Theory of Gases and Liquids" — Wiley.
3. Eucken, A., Phys. Feit. 12, 1101 (1911).
4. Kannuluik and Martin, Proc. Roy. Soc. (London) 144 A, 496, (1934).
5. Glassman and Bonilla, Chem. Eng. Prog. Symp. Ser. No. 5 49, 153 (1953).
6. Keyes and Sandell, Trans. ASME 72, 767 (1950).
7. Vines, R. G., Trans. ASME Jour. of Heat Trans. 82, 48 (1960).
8. Levinson, L. E., M. S. Thesis, Univ. of Calif. Berkeley, Dept. of Mech. Engr. (1956).
9. Eckert and Irvine, Jour. of Applied Mech. 25 (1957).
10. "Thermodynamic and Transport Properties of Gases" NBS Circular 564 (1955).
11. Vasilesco, V. Ann. Phys. 11, 20, 292 (1945).
12. Schilling, W. E. and Laxton, A. E., Phil. Mag. 7 10 721, 1930 (270 - 1100°K)(31 points).
13. Fortier, A., Compt. rend. 203, 711, 1936; 208, 506 (1939).
14. Fisher, W. J., Phys. Rev. 1 28, 73 (1909).
15. Grindley, J. H. and Gibson, A. H., Proc. Roy. Soc. (London) A 80, 114, 1908 (270 - 370°K)(9 points).
16. Sutherland, B. P. and Maass, O., Can. J. Research 6, 428 (1932).
17. Trantz, M. and Ludewigs, W., Ann. Physik 5 3, 409 (1929).
18. Edwards, R. W. and Rankins, A. D., Proc. Roy. Soc. (London) A 117, 245 (1927).
19. Titani, T. Bull. Chem. Soc. Japan 4, 68 (1929)(300 - 400°K)(5 points).

20. Johnston, H. L. and McCloskey, K. E., J. Phys. Chem. 44, 1038 (1940).
21. Wobser, R. and Muller, F., Kolloid-Beih 52, 65 (1941).
22. Bearden, J. A., Phys. Rev. 56, 1023 (1939).
23. Kestin and Wong, Trans. ASME 80, 11 (1958).
24. Kestin and Persen, "Molecular Theory of Gases and Liquids" - Wiley.
25. Michels and Gibson, Proc. Roy. Soc. (London) A 134, 288 (1931).
26. Uhler, A., Jr., J. Chem. Phys. 20, 463 (1952).
27. Warburg and Babo, V., Wied. Ann. 17, 390 (1882).
28. Taylor, W. J. and Johnston, H. L., J. Chem. Phys. 14, 219 (1946)
90 - 370°K (18 points).
29. Sherratt, G. G. and Griffith, E., Phil. Mag. 7 27, 68 (1939).
30. Milverton, S. W., Phil. Mag. 7 17, 397 (1934).
31. Mann, W. B. and Dickins, B. G., Proc. Roy. Soc. (London) A 134, 77 (1931) 270°K (6 points).
32. Schneider, E., Ann. Physik 4 79, 177 (1926).
33. Eucken, A., Physik Z. 12, 1101 (1911).
34. Stops, D. W., Nature (London) 164, 966 (1949).
35. Granet, I., and Kass, P., Petroleum Refiner 10, 113 (1952).
36. Biles, M. B. and Putnam, J. A., NACA TN 2783 (1952).
37. Bromley, L. A., UCRL-1852 (1952).
38. Lenoir, J. M., Ph. D. Thesis, Chem. Eng., University of Illinois (1949).
39. Franck, E. V., Chem. Ing. Tech. 25, 238 (1953).
40. Kannuluik, W. G. and Donald, H. B., Australian J. Sci. Res. 3A, 417 (1950).
41. Comings, E. W. and Nathan, M. F., Ind. Eng. Chem. 39, 964 (1947).

42. Gamson, Chem. Eng. Prog., Feb. 1949 pp. 154-159.
43. Uyehara, O. and Watson, Nat'l. Pet. News, Tech. Sect. Oct. 4, 1944.
44. Touloukian, Y. S., Ed., "The Retrieval Guide to Thermophysical Properties Research Literature," McGraw-Hill, New York (1960).

VII. SUPPLEMENTARY BIBLIOGRAPHY

The supplementary bibliographies (A. Viscosity and B. Thermal Conductivity) are from "Retrieval Guide for Thermophysical Properties Research Literature," Y. S. Touloukian, Ed.⁴⁴ By permission of the Purdue Research Foundation, Lafayette, Indiana.

A. Viscosity

Furber, B. N., "Heat-and-Mass-Transfer Experiments on Humid Air in Turbulent Flow Over a Plane Containing an Isolated Cooled Region," Proc. Inst. Mech. Engrs., London (1954).

Nicklin, A. W., "Thermal Properties of Carbon Dioxide, Nitrogen, Air, Hydrogen, and Helium," U. K. Atomic Energy Authority Ind. Group Tech. Note (1956).

Bromley, LeRoy A., "Thermal Conductivity of Gases at Moderate Pressures," USGPO, (UCRL-1852) (1952).

Keyes, F. G., "A Summary of Viscosity and Heat-Conduction Data for Helium, Argon, Hydrogen, Oxygen, Nitrogen, Carbon Monoxide, Carbon Dioxide, Water Vapor, and Air," Trans. Am. Soc. Mech. Engrs. (1951).

Hilsenrath, Joseph, Beckett, Charles W., Benedict, Wm. S., Fano, Lilla, Hoge, Harold J., Masi, Joseph F., Nuttall, Ralph L., Touloukian, Yeram S., and Woolley, Harold W., "Tables of Thermal Properties of Gases," USGPO, NBS Circ. 564 (1955).

Hilsenrath, Joseph and Touloukian, Y. S., "The Viscosity, Thermal Conductivity, and Prandtl Number for Air, Oxygen, Nitrogen, Nitric Oxide, Hydrogen, Carbon Monoxide, Carbon Dioxide, Water, Helium, and Argon," Trans. Am. Soc. Mech. Engrs. (1954).

Granet, Irving and Kass, Philip, "The Viscosity, Thermal Conductivity, and Specific Heat of Dry Air at Elevated Pressures and Temperatures," Petroleum Refiner (1952).

Godridge, A. M., "Some Properties of Gas Mixtures," Bull. Brit. Coal Utilization Research Assoc. (1954).

Hopper, V. D. and Laby, T. H., "The Electronic Charge," Proc. Roy. Soc., London (1941).

Hervasio, Guimaraes De Carvalho, "Variation of the Viscosity of Air with Temperature," Anais Assoc. Guim Brasil (1945).

Codegone, Cesare, "The Prandtl Numbers of Refrigerants," Inst. Intern. Froid Journees Mons Belg. Communs. (1953).

Kellstrom, Gunnar, "Note on a Paper a New Determination of the Viscosity of Air by the Rotating-Cylinder Method," Phil. Mag. (1941).

Vasilesco, Virgile, "Experimental Research on the Viscosity of Gases at High Temperatures," Ann. Phys. (1945).

Stolyarov, E. A., "Transfer Phenomena in Compressed Gases, III. An Empirical Equation of the Relation of the Viscosity of Compressed Gases to Temperature and Pressure," Zhur. Fiz. Khim. (1950).

Rudenko, N. S., "Viscosity of Liquid Oxygen, Nitrogen, Methane, Ethylene, and Air," J. Exptl. Theoret. Phys., USSR (1939).

Majumdar, V. D. and Oka, V. S., "Atomic Functions of Some Gases in the Light of Revised Viscosity Determinations," J. Univ. Bombay (1949).

Kompaneets, V. Ya, "Experimental Determination of the Viscosity of Gases and Gaseous Mixtures at High Temperatures," Sbornik Nauch Rabot Leningrad Inst. Mekhanizatsii Selsk Khoz (1953).

Johnston, Herrick L. and McCloskey, Kenneth E., "Viscosities of Several Common Gases Between 90°K and Room Temperature," J. Phys. Chem. (1940).

Isasaki, Hiroji, "Measurement of Viscosities of Gases at High Pressure. 1. Viscosity of Air at 50 Degrees, 100 Degrees, and 150 Degrees up to 200 Atm.," Science Repts. Research Insts. Tohoku Univ. (1951).

Brundt, A. W., "Properties of Hydrogen Mixtures," Trans. Am. Soc. Mech. Engrs. (1940).

Codegone, Cesare, "Dynamic Viscosity of Gases and Vapors," Atti. Accad. Sci. Torino Classe Sci. Fis. Mat. E. Nat. (1951).

Bromley, L. A. and Wilke, C. R., "Viscosity Behavior of Gases," Ind. Eng. Chem. (1951).

Dommett, R. L. "Thermodynamic Properties of Air at High Temperatures," Min. of Supply London (RAE-TN-GW-429) and Astia (AD-115386) (1956).

Kestin, J. and Wang, Hung-EN, "The Viscosity of Five Gases. A Re-Evaluation," Brown Univ. (AFOSR-TN-56-98) and Astia (AD-82011).

Makita, Tadashi, "The Viscosity of Argon, Nitrogen and Air at Pressures up to 800 KG/CM to the Second Power," Review of Physical Chemistry of Japan (1957).

Kestin, J. and Wang, H. E., "The Viscosity of Five Gases. A Re-Evaluation," ASME Transactions (1958).

Newman, Betty O., "Physical Properties of Heat Transfer Fluids," Gen. Eng. & Consulting Lab., GE and Astia (AD-64951) (1947).

Kellstrom, G., "Die Innere Reibung Von Luft IM Druckgebiet 1-30 KG/CM," Ark. Mat. Astr. Fys. (1941).

Naiki, Toshio, Hanai, Tetsuya and Shimizu, Sakae, "Measurement of the Viscosity of Liquid Air," Bull. Inst. Chem. Research, Kyoto Univ. (1932).

Othmer, Donald F., "Correlation Entre Les Donnees Physiques Et Chimiques, L Usage De L Industrie Chimique," Chim. and Ind. (1948).

Glassman, Irvin and Bonilla, Charles F., "Thermal Conductivity and Prandtl Number of Air at High Temperatures," Chem. Eng. Progr. Symp. Ser. (1953).

Fortier, Andre, "La Viscosite De L Air Et La Charge Electronique," Compt. Rend. (1939).

Fortier, Andre, "Physique. - Sur La Determination De La Viscosite Des Gaz Et De La Constante De Sutherland," Compt. Rend. (1936).

Withers, J. G., "Simplified Measurement of Gas Flow With Sharp Edged Orifices," The Engineer (1950).

Lohrische, F. W. , "Heat-Transfer Coefficients for Industrial Gases," J. Appl. Chem. London (1952).

Greifinger, P. S. , "Transport Coefficients of Dissociating and Slightly Ionizing Air," RAND (RM-1794) and USAF (AD-133002) (1957).

Aerodynamics Handbook Staff, "Handbook of Supersonic Aerodynamics, Vol. 5, Sec. 15, Properties of Gases," USGPO and NAVORD Rpt. 1488 (1953).

Hansen, C. Frederick, "Approximations for the Thermodynamic and Transport Properties of High-Temperature Air," AAL (NACA-TN-4150) (1958).

Rigden, P. J. , "The Viscosity of Air, Oxygen, and Nitrogen," Phil. Mag. (1938).

Shilling, W. G. and Laxton, A. E. , "The Effect of Temperature on the Viscosity of Air," Phil. Mag. (1930).

Golubev, I. F. , "Viscosity of Gases and Gas Mixtures at High Pressures," J. Tech. Phys. USSR (1938).

Carman, P. C. , "Diffusion and Flow of Gases and Vapours Through Micropores. 1. Slip Flow and Molecular Streaming," Proc. Roy. Soc. , London (1950).

Codegone, Cesare, "Viscosity of Gases and Vapors," Ricerca Sci. (1952).

Williams, Frank Archer, "The Effect of Temperature on Viscosity of Air," Proc. Roy. Soc. , London (1926).

Majumdar, V. D. and Vajifdar, M. B. , "Coefficient of Viscosity of Air," Proc. India Acad. Sci. (1938).

Edwards, R. S. and Rankine, A. O. , "On the Effect of Temperature on the Viscosity of Air," Proc. Roy. Soc. , London (1927).

Johnston, Herrick L. , Mattox, Robert W. and Powers, Robert W. , "Viscosities of Air and Nitrogen at Low Pressures," Ohio State Univ. and NACA (NACA-TN-2546) (1951).

Kestin, J. and Leidenfrost, W., "The Effect of Moderate Pressures on the Viscosity of Five Gases. From Thermodynamics and Transport Properties of Gases, Liquids and Solids," ASME Symp. on Thermal Properties (1959).

Trautz, Max and Binkele, H. E., "Die Reibung, Wärmeleitung Und Diffusion in Gasmischungen. VIII. Die Reibung Des H_2 , He, Ne, A Und Ihrer Binaren Gemische," Ann. Physik (1930).

Trautz, Max and Zink, Robert, "Die Reibung, Wärmeleitung Und Diffusion in Gasmischungen. XII. Gasreibung Bei Hoheren Temperaturen," Ann. Physik (1930).

Vogel, Hans, "Über Die Viskosität Einiger Gase Und Ihre Temperaturabhängigkeit Bei Tiefen Temperaturen," Ann. Physik (1914).

Giile, Arthur, "Die Koeffizienten Der Inneren Reibung Bei Gemischen Von Helium Und Wasserstoff," Ann Physik (1915).

Tribus, Myron and Boelter, L. M. K., "An Investigation of Aircraft Heaters. II. Properties of Gases," NACA Aero Rept. W-9 (1946).

Boelter, L. M. K. and Sharp, W. H., "An Investigation of Aircraft Heaters. XVI. Determination of the Viscosity of Exhaust Gases from a Gasoline Engine," NACA Aero Rept. W-22 (1946).

Schuil, A. E., "Note on the Viscosity of Gases and Molecular Mean Free Path," Phil. Mag. (1939).

Biles, Martin B. and Putman, J. A., "Use of a Consolidated Porous Medium for Measurement of Flow Rate and Viscosity of Gases at Elevated Pressures and Temperatures," UC and NASA (NACA-TN-2783) (1952).

Bauer, E. and Zlotnick, M., "Transport Coefficients of Air to 8000 K," Avco Research and Development Division (RAD-TR-58-12) (1958).

Stolyarov, E. A., "Transfer Phenomena in Compressed Gases. III. Empirical Equation for the Dependence of the Viscosity of Compressed Gases on Temperature and Pressure." English Trans. TIB/T4490, Zhur. Fiz. Khim. (1950).

States, M. N., "Determination of Viscosity of Helium and the Coefficients of Slip of Helium and Oxygen by the Constant Deflection Method," Phys. Rev. (1923).

Bearden, J. A., "A Precision Determination of the Viscosity of Air," (1939).

Bentley, Robert, Brown, George, and Schlegal, Richard, "Physical Constants of Proposed Coolants," Metall. Lab. Univ. Chicago and AEC OTS (CP-3061) (1945).

B. Thermal Conductivity

Kannuluik, W. G. and Donald, Heather B., "The Pressure Dependence of the Thermal Conductivity of Polyatomic Gases at 0 Degrees," Australian J. Sci. Research (1950).

Abas-Zade, A. K., "Measurement of the Heat Conductivity of Liquids and Vapors at High Temperatures and Pressures," Doklady Akad Nauk Azerbaidzhan SSR (1947).

Furber, B. N., "Heat and Mass-Transfer Experiments on Humid Air in Turbulent Flow Over a Plane Containing an Isolated Cooled Region," Proc. Inst. Mech. Engrs., London (1954).

Schmidt, Ernst and Leiendfrost, W., "Heat Transport in Liquid Non-conductors Under the Influence of Electric Fields," Chem. Ing. Tech. (1954).

Schlinger, W. G., Hsu, N. T., Cavers, S. D., and Sage, B. H., "Temperature Gradients in Turbulent Gas Streams," Ind. Eng. Chem. (1953).

Rothman, Albert Joel, "Thermal Conductivity of Gases at High Temperatures," USGPO (UCRL-2339) and Astia (AD-20618).

Nicklin, A. W., "Thermal Properties of Carbon Dioxide, Nitrogen, Air, Hydrogen, and Helium," U. K. Atomic Energy Authority Ind. Group Tech. Note (TG-TN-36) (1956).

Kersten, J. A. H., "Relation Between the Thermal Conductivity of Rarefied Gases and the Sensitivity Range of Pirani Gages," Physica (1948).

Ishikawa, Fusao and Yagi, Katora, "Application of Thermal Conductivity of Mixed Gases. IV. Thermal Conductivity of Carbon Monoxide-Carbon Dioxide and Air-Acetone Binary Systems," Bull. Inst. Phys. Chem. Research (1943).

Bromley, LeRoy A. , "Thermal Conductivity of Gases at Moderate Pressures," USGPO (UCRL-1852) (1952).

Eckert, E. R. G. and Irvine, T. F. , Jr. , "New Method for Measurement of Prandtl Number and Thermal Conductivity of Fluids," J. Appl. Mechanics (1957).

Stops, D. W. , "Effect of Temperature on the Thermal Conductivity of Gases," Nature (1949).

Cooper, A. , "Expanded Rubber as a Thermal-Insulating Material," Trans. Inst. Rubber Ind. (1951).

Hougen, Joel O. and Piret, Edgar L. , "Effective Thermal Conductivity of Granular Slides Through Which Gases are Flowing," Chem. Eng. Progress (1951).

Keyes, F. G. , "A Summary of Viscosity and Heat-Conduction Data for Helium, Argon, Hydrogen, Oxygen, Nitrogen, Carbon Monoxide, Carbon Dioxide, Water Vapor, and Air," Trans. Am. Soc. Mech. Engrs. (1951).

Baxter, S. , Vodden, H. A. and Davies, S. , "Thermal Conductivity of Organic Liquids for Use in Heat-Transfer Calculations," J. Appl. Chem. , London (1953).

Riedel, L. , "Thermal Conductivity Measurements on Sugar Solutions, Fruit Juices, and Milk," Chemis. Ing. Tech. (1949).

Callear, A. B. and Robb, James, C. , "An Experimental Method of Measuring the Thermal Conductivity of Gases," Trans. Faraday Soc. (1955).

Awano, Mitsuku, "The Thermal Conductivity of Imperfect Gases," Busseiron Kenkyu (1951).

Stolyarov, E. A. , Ipatev, V. V. and Theodorovich, V. P. , "Transfer Phenomena in Compressed Gases. I. Determination of the Heat-Conductivity Coefficients of Compressed Gases (Hydrogen, Nitrogen, Air, Methane, and Carbon Dioxide)," Zhur. Fiz. Khim. (1950).

Vargaftik, N. B. and Oleshchuk, O. N. , "The Temperature Dependence of the Heat Conductivity of Gases," 12 Vest VTi (1946).

Hilsenrath, Joseph, Beckett, Charles W. , Benedict, Wm. S. , Fano, Lilla, Hoge, Harold, Jr. , Masi, Joseph F. , Nuttall, Ralph L. , Touloukian, Yeram S. and Woolley, Harold W. , "Tables of Thermal Properties of Gases," USGPO and NBS Circ. 564 (1955).

Franck, E. U. , "Thermal Conductivity in Highly Compressed Gases," Chem. Ing. Tech. (1953).

Schmidt, A. F. and Spurlock, B. H. , Jr. , "The Thermal Conductivity of Fluids," Trans. Am. Soc. Mech. Engrs. (1954).

Hilsenrath, Joseph and Touloukian, Y. S. , "The Viscosity, Thermal Conductivity, and Prandtl Number for Air, Oxygen, Nitrogen, Nitric Oxide, Hydrogen, Carbon Monoxide, Carbon Dioxide, Water, Helium, and Argon," Trans. Am. Soc. Mech. Engrs. (1954).

Granet, Irving and Kass, Philip, "The Viscosity, Thermal Conductivity, and Specific Heat of Dry Air at Elevated Pressures and Temperatures," Petroleum Refiner (1952).

Godridge, A. M. , "Some Properties of Gas Mixtures," Bull. Brit. Coal Utilization Research Assoc. (1954).

Lambert, J. D. , Staines, E. N. and Woods, S. D. , "Thermal Conductivities of Organic Vapors," Proc. Roy. Soc. , London (1950).

Kirschfelder, J. O. , Bird, R. B. and Spots, Ellen L. , "Viscosity and Other Physical Properties of Gases and Gas Mixtures," Trans. Am. Soc. Mech. Engrs. (1949).

Codegone, Cesare, "The Prandtl Numbers of Refrigerants," Inst. Intern. Froid Journees Mons. Belg. Communs. (1953).

Taylor, Wm. J. and Johnston, Herrick L. , "An Improved Hot-Wire Cell for Accurate Measurements of Thermal Conductivities of Gases Over A Wide Temperature Range," J. Chem. Phys. (1946).

Brundt, A. W. , "Properties of Hydrogen Mixtures," Trans. Am. Soc. Mech. Engrs. (1940).

Kannuliuk, W. G. and Carman, E. H. , "The Temperature Dependence of the Thermal Conductivity of Air," Austral. J. Sci. Res. Ser. A. (A-305-14) (1951).

Kharbanda, Om P. , "Thermal Conductivity Chart for Gases," Chem. Eng. (1955).

Peck, Ralph E. and Lokay, Joseph D. , "Accommodation Coefficients and Thermal Conductivities of Hydrogen, Helium, Air and Argon for Chrome Surfaces at Reduced Pressures." Tech. Rept. #1, Astia (AD-62517) (1955).

Dommett, R. L. , "Thermodynamic Properties of Air at High Temperatures," Min. of Supply London (RAE-TN-GW-429) and Astia (AD-115386) (1956).

Newman, Betty O. , "Physical Properties of Heat Transfer Fluids," Gen. Eng. & Consulting Lab, GE and Astia (AD-64951) (1947).

Weber, Sophus, "Uber Die Warmeleitfahigkeit Der Gase," Ann. Physik (1927).

Glassman, Irvin and Bonilla, Charles F. , "Thermal Conductivity and Prandtl Number of Air at High Temperatures," Chem. Eng. Progr. Symp. Ser. (1953).

Lohrisch, F. W. , "Heat-Transfer Coefficients for Industrial Gases," J. Appl. Chem. , London (1952).

Waelbroeck, F. G. and Zuckerbrodt, P. , "Thermal Conductivities of Gases at Low Pressures," J. Chem. Phys. (1958).

Allcut, E. A. , "Thermal Conductivity Tests and Results," J. Inst. Heating Ventilating Eng. (1949).

Greifinger, P. S. , "Transport Coefficients of Dissociating and Slightly Ionizing Air," RAND (RM-1794) and Astia (AD-133002) (1957).

Aerodynamics Handbook Staff, "Handbook of Supersonic Aerodynamics, Vol. 5, Sec. 15, Properties of Gases," USGPO and NAVORD Rpt. 1488 (1953).

Hansen, C. Frederick, "Approximations for the Thermodynamic and Transport Properties of High-Temperature Air," AAL (NACA-TN-4150) (1958).

Kannuluik, W. G. and Martin, L. H. , "Conduction of Heat in Powders," Proc. Roy. Soc. , London (1933).

Boelter, L. M. K. and Sharp, W. H., "An Investigation of Aircraft Heaters. XXXII. Measurement of Thermal Conductivity of Air of Exhaust Gases Between 50 and 900 °F," UC(NASA-TN-1912) (1949).

Lander, Robert, "Effect of Surface Resistance on Thermal Conductivity by the Hot Plate Method," Univ. Minn. Inst. Technol. Eng. Exp. Sta. Tech. Paper (1942).

Hansen, C. Frederick and Heims, Steve P., "Chemical Reaction Rate Properties of High Temperature Air," AALNACA (NACA-TN-4359) (1958).

Christiansen, C., "III. Einige Versuche Uber Die Warmeleitung," Ann. Physik (1881).

Eckert, E. R. G., Ibele, W. E. and Irvine, T. F., Jr., "Thermal Conductivity of Helium-Air Mixtures. From Thermodynamic and Transport Properties of Gases, Liquids, and Solids," ASME Symp. on Thermal Properties (1959).

Winkelmann, A., "IV. Neue Versuche Uber Die Abhangigkeit Der Warmeleitung Der Gase Von Der Temperatur," Ann. Physik (1886).

Boelter, L. M. K. and Sharp, W. H., "An Investigation of Aircraft Heaters. XVI. Determination of the Viscosity of Exhaust Gases From a Gasoline Engine," NACA Aero Rept. W-22 (1946).

Mann, W. B. and Dickins, B. G., "Thermal Conductivities of the Saturated Hydrocarbons in the Gaseous State," Proc. Roy. Soc., London (1931).

Kayan, C. F. and Glaser, P. E., "A Transient Method of Measuring Thermal Properties of Insulating Materials," Congr. Intern. Froid 9E Paris 1955 Compt. Rend. Trav. Comm. (1955).

Eucken, A., "On the Temperature Dependency of the Thermal Conductivity of Several Gases," Physik Z. (1911).

Dickins, B. G., "The Effect of Accommodation on Heat Conduction Through Gases," Proc. Roy. Soc., London (1934).

Markwood, W. H., Jr. and Benning, A. F., "Thermal Conductances and Heat Transmission Coefficients of Freon Refrigerants," Refrig. Eng. (1943).

Bentley, Robert, Brown, George and Schlegal, Richard, "Physical Constants of Proposed Coolants," Metall. Lab. Univ. Chicago and AEC OTS (CP-3061) (1945).

Przybycien, W. M. and Linde, D. W. , "Thermal Conductivities of Gases, Metals, and Liquid Metals," USAEC OTS (KAPL-M-WMP-1) (1957).

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.